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6 Strategies for Control of Lattice Architecture in Low-Dimensional Molecular Metals: Assembly of Partially Oxidized Face-to-Face Linked Arrays of Metallomacrocycles.

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STRATEGIES FOR CONTROL OF LATTICE ARCHITECTURE IN LOW-DIMENSIONAL
MOLECULAR METALS: ASSEMBLY OF PARTIALLY OXIDIZED FACE-TO-FACE
LINKED ARRAYS OF METALLOMACROCYCLES.

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ABSTRACT

This paper discusses an approach to control molecular stacking interactions in low-dimensional mixed valence materials by locking partially oxidized metallomacrocycles together in a face-to-face orientation. Thus, doping of the cofacially linked oligomers $[M(Pc)O]_n$ ($M = Si, Ge, Sn$; $Pc =$ phthalocyaninato) with halogen (I_2, Br_2) or quinone (e.g., TCNQ, DDQ) electron acceptors produces robust, electrically conductive polymers with a wide range of stoichiometries and properties. The new materials have been studied by a variety of physical methods including X-ray diffraction, resonance Raman and infrared spectroscopy, ESR, static magnetic susceptibility, and variable-temperature four-probe electrical conductivity. Evidence is presented that some of the polymers have "metal-like" conductivity in the stacking direction and that transport properties within the series can be readily manipulated by rational variation of lattice architecture (e.g., the identity of the metal, M) and acceptor characteristics. Additional information is presented on doping experiments with electron donors and on employing metallohemiporphyrazines as polymer building blocks.

INTRODUCTION

The past half-dozen years have witnessed intense scientific activity in the area of low-dimensional electrically conductive materials [1-5]. Great excitement has been generated among chemists and physicists by the synthesis and properties of unusual

organic and metal-organic substances with metal-like properties. These developments can be anticipated to lead ultimately to new degrees of chemical control over collective solid state properties, to new methodology in chemical synthesis and in physical measurements, and to better theoretical models for cooperative phenomena in condensed matter. In the technological sphere, this research may lead to a new generation of electronic materials with applications as varied as sensors, rectifiers, fuel cell components, solar energy conversion elements, and electrophotographic devices. The possibility of high temperature superconductors or at least highly conductive synthetic materials which could replace metals in various applications, has contributed additional impetus to the design and study of metal-like materials.

Despite the advances that have been achieved, it is fair to say that our understanding of those molecular and electronic characteristics which control charge conduction is at a rather primitive level. That is also true of the synthetic chemical methodology required to tailor structures for testing current theories about the molecular metallic state or for optimizing materials performance and processing characteristics. A tremendous challenge exists in learning to control these factors, and the purpose of this article is to report on new developments in our Laboratory which address a number of chemical and physico-chemical aspects of this problem.

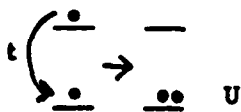
STRATEGIES FOR THE DESIGN OF HIGHLY CONDUCTIVE LOW-DIMENSIONAL MATERIALS

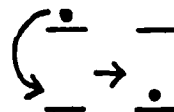
Two features now appear to be necessary for facile charge conduction in a molecular material [6,7]. First, the component molecules must be arrayed in close spatial proximity, with sufficient

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Unoxidized

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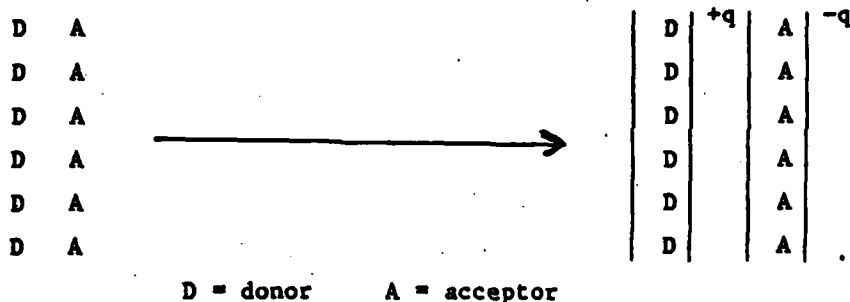


t = transfer integral = bandwidth/4

FIGURE 1. Schematic illustration of the effect of partial oxidation on charge mobility in a low-dimensional system composed of molecular stacks.

model [1-5], this requirement reflects the relatively narrow bandwidths ($4t$) and large on-site Coulomb repulsions (U) in such systems. A simplified valence bond picture of this situation is illustrated in Figure 1; partial oxidation facilitates charge mobility by creating numerous electronic vacancies. A similar picture could be constructed for partial reduction.

A successful, first-generation strategy for the synthesis of mixed valent low-dimensional materials [6,7] has involved the co-crystallization of planar, conjugated metallomacrocylic donor molecules (D) with halogen acceptors (A) as schematized below.



In optimum cases, the result has been lattices composed of segregated, partially oxidized metallomacrocylic stacks and parallel arrays of halide or polyhalide counterions [6-8]. An important additional feature of this approach is that the form of the halogen (even if disordered) can be straightforwardly determined by resonance Raman/iodine Mossbauer spectroscopic techniques [6-11]. The degree of partial oxidation follows from this information and knowledge of the stoichiometry. This synthetic approach has enjoyed success for metal glyoximates [8,12,13], dibenzotetraazaannulenes [14], phthalocyanines [15-17], and porphyrins [18]. The crystal structure of an example, nickel phthalocyanine iodide ($[\text{Ni}(\text{Pc})]\text{I}_{1.0}$) [15-17], is illustrated in Figure 2. The 300°K conductivity of this material in the

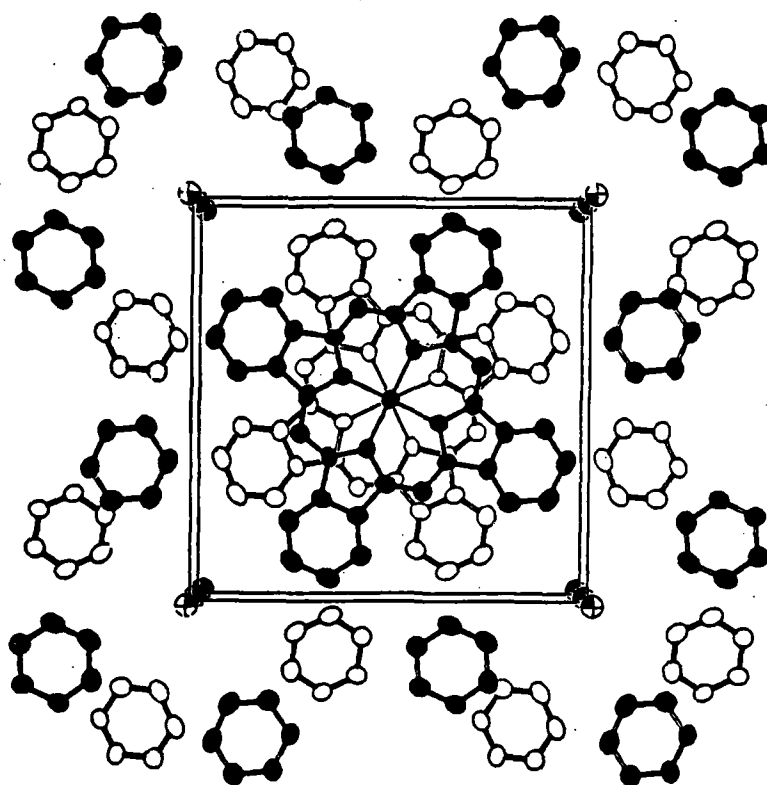


FIGURE 2. The crystal structure of nickel phthalocyanine iodide, $[\text{Ni}(\text{Pc})]\text{I}_{1.0}$, viewed along the stacking direction. From ref. 7.

molecular stacking direction ($300\text{--}700\ \Omega^{-1}\text{ cm}^{-1}$) is high (carrier mean free paths are comparable to some of the most conductive "molecular metals") and the temperature dependence is "metal-like" ($\rho \sim T^{1.9}$) down to 60° K .

Although the above strategy is frequently effective, it suffers, as do all approaches based upon simple molecular

stacking, from the weakness that the lattice architecture is totally dependent upon the unpredictable and largely uncontrollable forces that dictate the stacking pattern, the donor-acceptor orientations, and the stacking repeat distances. Figure 3 illustrates the complexity of the structural problem by depicting some of the types of crystallization patterns which have been identified. A common pitfall in the design of new materials

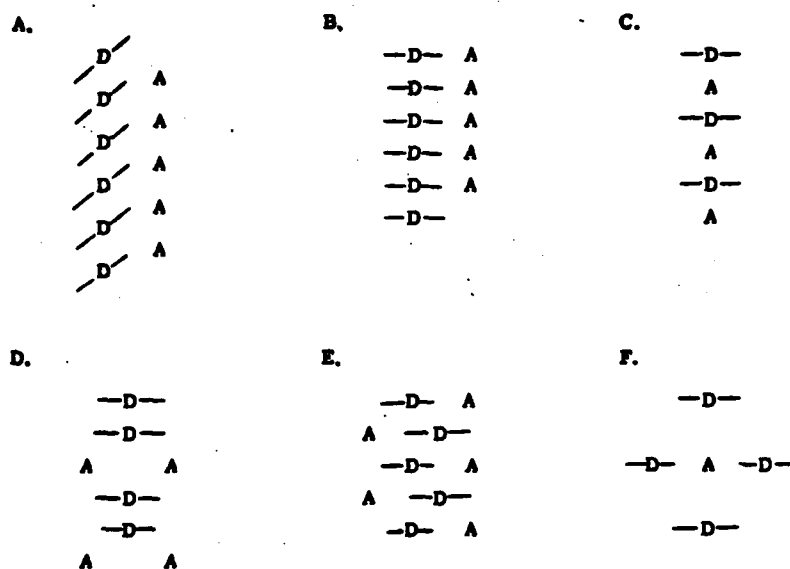


FIGURE 3. Schematic depiction of some common structures for donor-acceptor complexes. A. Segregated stacking, canted donors. B. Segregated stacking, D_{nh} donor stacking. C. Integrated stacking. D. Integrated stacking, donor dimers. E. Segregated stacking, zig-zag donor stacking. F. Ion clusters without stacking.

is the formation of integrated D-A stacks (3C,D), which invariably leads to insulators [2,6,19]. As an example, attempts to substitute oxidizing quinones for halogens in the aforementioned phthalocyanine chemistry lead to integrated stack insulators [20].

A successful new approach to the control of molecular stacking in low dimensional mixed valence materials is founded upon the construction of macromolecules in which arrays of metallomacrocycles are tightly locked in a "face-to-face" configuration by covalent bonds [21-23]. Followed by partial oxidation, this approach capitalizes upon a great deal of accumulated chemical and physical information about the subunits, and offers the real possibility of constructing robust new conductive polymers with well-defined and easily manipulated primary and secondary structures. The forces which hold the stacks together are now covalent linkages with bond energies on the order of 80-100 kcal/mol rather than weak packing, van der Waals, and bandwidth forces. As a result, it is now possible to both delve into those factors which stabilize the mixed valent state without fear of a breakdown in stacking, and to perturb systematically bandwidth and phonon dynamics. Although we focus our discussion primarily upon phthalocyanines (with additional remarks about hemiporphyrazines), it should be clear that the strategy has obvious generality.

SYNTHESIS AND PROPERTIES OF FACE-TO-FACE LINKED METALLO-PHTHALOCYANINES

The Group IVA precursor phthalocyanines $\text{Si}(\text{Pc})\text{Cl}_2$, $\text{Ge}(\text{Pc})\text{Cl}_2$, and $\text{Sn}(\text{Pc})\text{Cl}_2$ were synthesized as described elsewhere [22,24-26]. Hydrolysis in pyridine/NaOH solution converts the dichlorides to the corresponding dihydroxides, $\text{Si}(\text{Pc})(\text{OH})_2$, $\text{Ge}(\text{Pc})(\text{OH})_2$, $\text{Sn}(\text{Pc})(\text{OH})_2$ [22,24-26]. Condensation of these compounds to form

phthalocyaninato polysiloxanes, polygermyloxanes, and polystannyloxanes (Figure 4) was carried out at 300-400°C/10⁻³ torr [22,24-26]. The resulting macromolecules have been characterized by a broad range of chemical and physicochemical methods. These [M(Pc)O]_n materials have high chemical and thermal stability; moreover, they are not significantly degraded by oxygen or moisture. The polysiloxane polymer can be dissolved in concen-

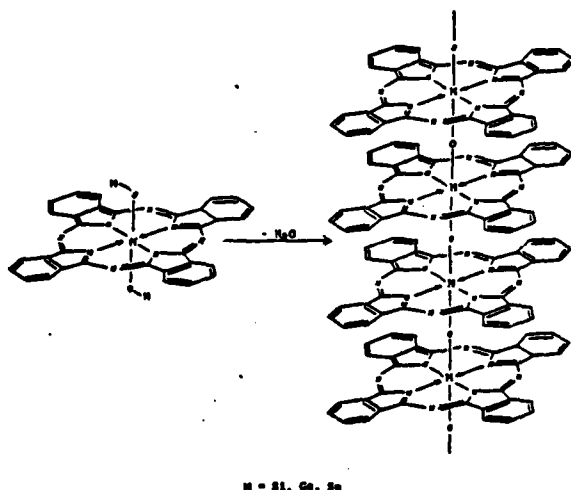


FIGURE 4. Condensation reaction to produce cofacial arrays of Group IV metallophthalocyanines.

trated sulfuric acid and recovered unchanged (typical of phthalocyanines containing non-electropositive metals). A rough estimate of the minimum average chain length of [Si(Pc)O]_n produced in the condensation polymerization can be obtained by infrared spectrophotometric analysis of the Si-O stretching region. For a typical

sample, the degree of polymerization is estimated to be on the order of ca. 100 subunits or more. Structural information on the face-to-face polymers can be derived from several lines of evidence. X-ray powder diffraction patterns can be indexed in the tetragonal crystal system [21,22,24] and are very similar to the patterns exhibited by the columnar crystal structures of $[\text{Ni}(\text{Pc})]\text{I}_{1.0}$ [17] and $\text{Ni}(\text{dpg})_2\text{I}_{1.0}$ (dpg = diphenylglyoximate) [8]. The stacking intervals ($c/2$) in these latter tetragonal structures, determined in single crystal studies, are 3.244(2) Å and 3.271(1) Å, respectively. The stacking intervals derived for the $[\text{M}(\text{Pc})\text{O}]_n$ materials from the powder diffraction data are found to depend upon the ionic radius of the Group IV ion and vary from 3.33(2) Å (Si-O-Si) to 3.51(2) Å (Ge-O-Ge), to 3.95(2) Å (Sn-O-Sn) [21,22,24]. These relationships are illustrated in Figure 5. The

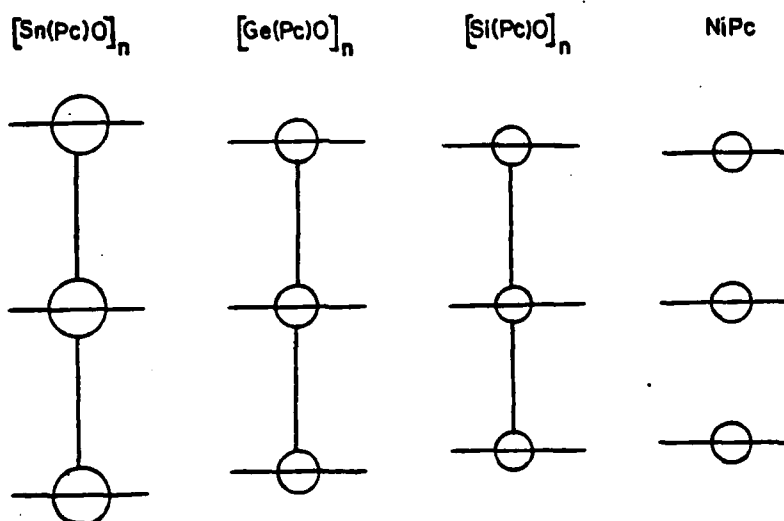


FIGURE 5. Scale drawing of the interplanar relationships in the face-to-face phthalocyanine polymers and in $[\text{Ni}(\text{Pc})]\text{I}_{1.0}$.

reliability of these metrical parameters is further supported by single crystal diffraction results on the model trimer $[(CH_3)_3SiO]_2(CH_3)SiO[Si(Pc)O]_3Si(CH_3)[OSi(CH_3)_3]_2$ which contains three cofacial $Si(Pc)O$ units linked by linear $Si-O-Si$ connections at a distance of $3.324(2) \text{ \AA}$ [27]. In addition, the $[Ge(Pc)O]_n$ and $[Sn(Pc)O]_n$ interplanar spacings obtained from diffraction data are in good agreement with values estimated from ionic radii [28] assuming linear $Ge-O-Ge$ and $Sn-O-Sn$ vectors, i.e., 3.58 \AA for $[Ge(Pc)O]_n$ and 3.90 \AA for $[Sn(Pc)O]_n$ [21,22,24]. There is good precedent for molecules with linear $Si-O-Si$, $Ge-O-Ge$, and $Sn-O-Sn$ linkages [29]. The $[M(Pc)O]_n$ polymers display vibrational and optical spectra which are characteristic of metallophthalocyanines [24].

PARTIAL OXIDATION OF COFACIALLY LINKED METALLOPHthalOCYANINES WITH HALOGENS

Doping experiments on the $[M(Pc)O]_n$ polymers were first carried out using iodination methodology developed in this Laboratory for simple stacked systems [6,7]. Stirring the powdered polymers with solutions of iodine in organic solvents or exposing the powders to iodine vapor results in substantial iodine uptake. Alternatively, $[Si(Pc)O]_n$ can be doped by dissolving in sulfuric acid and precipitating with an aqueous I_3^- solution. The stoichiometries which can be obtained depend upon the reaction conditions; representative iodinated materials characterized by elemental analysis are compiled in the left-hand column of Table I. A survey experiment also indicated that bromine-doped material could be prepared. That partial oxidation of the cofacial array has indeed occurred is confirmed by resonance Raman scattering spectroscopy in the polyiodide region (Figure 6). The

TABLE 1

Physical Data for Polycrystalline Samples of Halogen-Doped
[M(Pc)O]_n Materials

Compound	$\sigma(\Omega^{-1}\text{cm}^{-1})300^\circ\text{K}$	Activation Energy (eV)	Interplanar Spacing (Å)
[Si(Pc)O] _n	3×10^{-8}		3.33(2)
[[Si(Pc)O]I _{0.50}] _n	2×10^{-2}		
[[Si(Pc)O]I _{1.55}] _n	1.4	0.04±0.001	3.33(2)
[[Si(Pc)O]I _{4.60}] _n	1×10^{-2}		
[[Si(Pc)O]Br _{1.00}] _n	6×10^{-2}		
[Ge(Pc)O] _n	<10 ⁻⁸		3.51(2)
[[Ge(Pc)O]I _{1.80}] _n	3×10^{-2}	0.08±0.006	3.51(2)
[[Ge(Pc)O]I _{1.90}] _n	5×10^{-2}	0.06±0.003	
[[Ge(Pc)O]I _{1.94}] _n	6×10^{-2}	0.05±0.007	
[[Ge(Pc)O]I _{2.0}] _n	1×10^{-1}		
[Sn(Pc)O] _n	<10 ⁻⁸		3.95(2)
[[Sn(Pc)O]I _{1.2}] _n	1×10^{-6}		3.95(2)
[[Sn(Pc)O]I _{5.5}] _n	2×10^{-4}	0.68±0.01	
[Ni(Pc)]I _{1.0} ^a	7×10^{-1}	0.036±0.001	3.244(2)

^a Reference 15.

characteristic totally symmetric stretching frequency of I₃⁻ ($\nu = 108 \text{ cm}^{-1}$) [6,7,9] is observed along with an accompanying overtone progression. For samples with I/M < 3, there are at most only traces of I₅⁻ ($\nu \approx 160 \text{ cm}^{-1}$) [8,10] and no indication of free

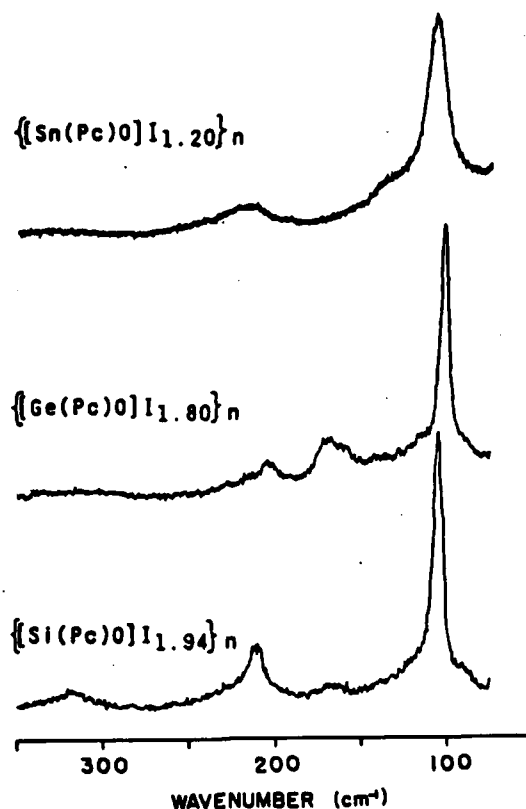


FIGURE 6. Resonance Raman spectra ($\nu_0 = 5145 \text{ \AA}$) of iodine-doped phthalocyanine face-to-face polymers. From ref. 21.

$I_2(\nu \approx 200 \text{ cm}^{-1})$ [8,10]. The nature of the $[M(Pc)O^{\delta+}]_n$ electronic structure was also studied by electron spin resonance (ESR). The symmetry of the lineshapes and the measured g -values are consistent with π -radical cations, i.e., the unpaired spin density is in molecular orbitals which are predominantly ligand in character [30]. A similar conclusion was reached for $[Ni(Pc)]I_{1.0}$ [17]. ESR data for the $\{[M(Pc)O]I_x\}_n$ materials are

compiled in Table 2. In regard to structural changes which might accompany doping, X-ray powder diffraction studies indicate that iodination does not significantly alter the interplanar separations [21,22,24].

TABLE 2

Powder ESR Data for Iodinated Phthalocyanine Face-to-Face Polymers

Compound	$g(300^\circ\text{K})^a$	$\Gamma(300^\circ\text{K})(G)^b$
$\{[\text{Si}(\text{Pc})\text{O}]\text{I}_{1.40}\}_n$	2.003	5.1
$\{[\text{Ge}(\text{Pc})\text{O}]\text{I}_{0.62}\}_n$	2.002	3.2
$\{[\text{Sn}(\text{Pc})\text{O}]\text{I}_{1.20}\}_n$	2.002	6.0

^a Average g -value; g_{\parallel} and g_{\perp} are not resolved.

^b Observed linewidth.

Four-probe electrical conductivity measurements on the $[\text{M}(\text{Pc})]_n$ powders using locally developed van der Pauw techniques [31,32] show them to be insulators. However, iodine or bromine doping results in large increases in electrical conductivity (Table 1). The general trend in conductivity as a function of metal is $\sigma_{\text{Si}} \geq \sigma_{\text{Ge}} > \sigma_{\text{Sn}}$. Since the transport characteristics of iodine-oxidized metallophthalocyanines are known to be largely ligand-dominated and relatively insensitive to the identity of the metal [15-17], the metal dependence of the conductivity observed in the face-to-face polymers is logically ascribed to structural differences such as the interplanar separation. Indeed, the

$\{\text{Si}(\text{Pc})\text{O}\}\text{I}_x$ interplanar separation is within 0.1 Å of that in $[\text{Ni}(\text{Pc})]\text{I}_{1.0}$ and the room temperature powder conductivities of the two materials are comparable (Table 1). The temperature dependence of the $\{\text{M}(\text{Pc})\text{O}\}\text{I}_x$ powder conductivities is thermally activated (Figure 7), and least squares fits to Eq.(1) yield the

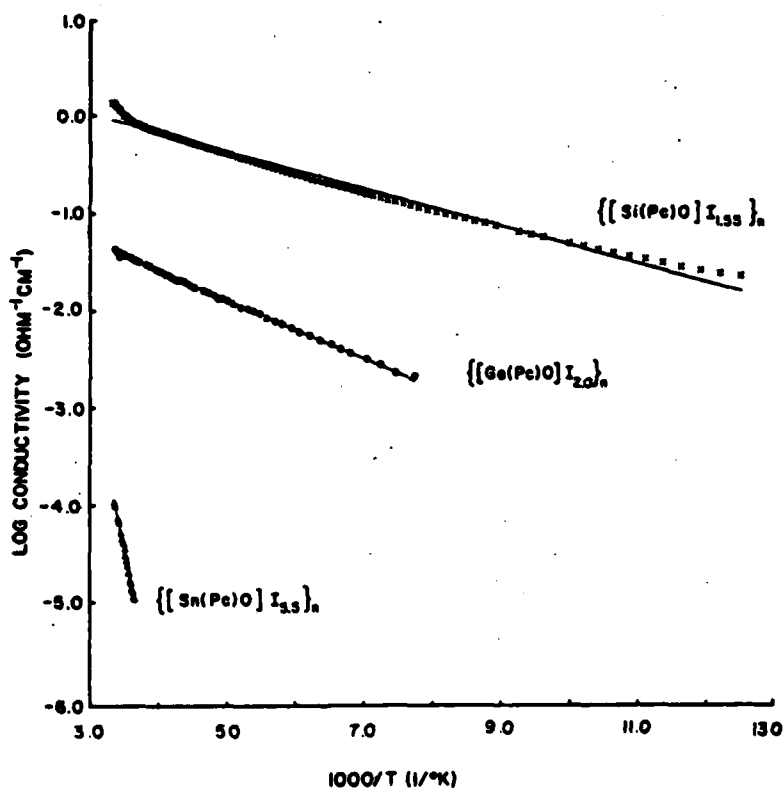


FIGURE 7. Variable temperature four-probe electrical conductivity data for powders of the iodine-doped, face-to-face phthalocyanine polymers.

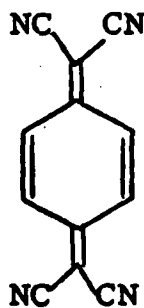
$$\sigma = \sigma_0 e^{-\Delta/kT} \quad (1)$$

activation parameters compiled in Table 1. Powder conductivities are, of course, affected by interparticle contact resistance and averaging over all crystallographic orientations. Thus, for low-dimensional "molecular metals" such as $[\text{Ni}(\text{Pc})]\text{I}_{1.0}$, powder conductivities are typically 10^2 - 10^3 less than single crystal conductivities in the stacking direction. Thus, "metal-like" temperature dependence is usually masked. From the powder data on the $\{[\text{M}(\text{Pc})\text{O}]\text{I}_x\}_n$ materials it can be anticipated that high, "metal-like" conductivities will be observed in the chain direction for the $\text{M} = \text{Si}$ and possibly $\text{M} = \text{Ge}$ materials. Voltage shorted compaction (VSC) techniques [33] offer an effective qualitative means to sample stacking axis transport properties in pressed powder samples by deliberately shorting out sources of interparticle resistance. In the present context it is important to note that the VSC conductivity behavior of $\{[\text{Si}(\text{Pc})\text{O}]\text{I}_x\}_n$ samples is unequivocally "metal-like" [34]. The results of the variable temperature conductivity studies also underscore the robust thermal character of the cofacially arrayed polymers. $\{[\text{Si}(\text{Pc})\text{O}]\text{I}_x\}_n$ samples could be cycled to 300°C with only a minor decrease in room temperature conductivity (due primarily to vaporization of the iodine).

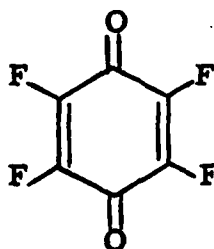
Static magnetic susceptibility by Faraday techniques reveals another characteristic signature [1-5] of "molecular metals" in the $\{[\text{Si}(\text{Pc})\text{O}]\text{I}_x\}_n$ and $\{[\text{Ge}(\text{Pc})\text{O}]\text{I}_x\}_n$ materials. Susceptibilities are only weakly paramagnetic ($\chi_M = 300$ - 500×10^{-6} emu after diamagnetic corrections are made) and are only modestly dependent on temperature down to 77°K [21,22]. Studies at lower temperatures are in progress.

RESPONSE OF THE COFACIALLY LINKED METALLOPHTHALOCYANINES TO OTHER DOPANTS

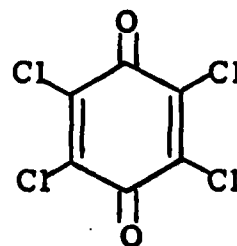
The strictly enforced molecular stacking in the $[M(Pc)O]_n$ materials offers an unprecedented opportunity to experiment with some of the important forces [2,6,35-39] which stabilize or destabilize the molecular metallic state. Thus, the electronic aspects of the donor-acceptor interaction can be studied with far greater control over the structural variables. It was first of interest to learn whether non-halogen oxidants could produce a partially oxidized, conductive metallophthalocyanine stack, or whether there was something "magic" about iodine and bromine. High potential quinones such as those shown below have electron affinities comparable to halogens, and produce conductive compounds with a



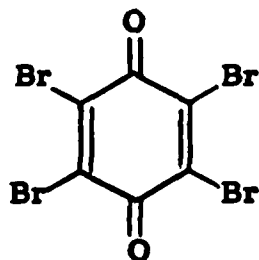
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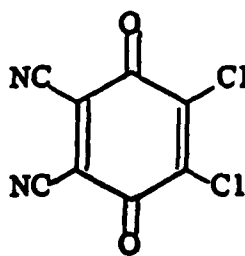
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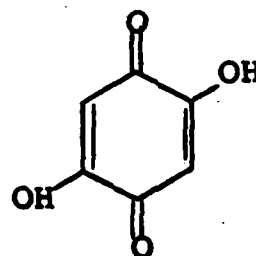
chloranil



bromanil



DDQ



DHB

number of organic donors [1-5]. With simple metallophthalocyanines, however, only insulators are produced [20] and considerable structural evidence points to an integrated stack crystal structure [40] as the reason for the low charge transport capability. It was thus of interest to determine what donor-acceptor interactions would occur in a metallophthalocyanine system which was locked into stacks. Doping experiments were conducted by stirring the $[\text{Si}(\text{Pc})\text{O}]_n$ macromolecules with solutions of the above quinones. The products were characterized by elemental analysis and vibrational spectroscopy. As can be seen in Table 3, large increases in electrical conductivity accompany the quinone doping. Indeed, the DDQ-doped materials are as conductive as many of the halogenated polymers [23,41]. The temperature dependence of the conductivity of some representative samples is shown in Figure 8. The transport in these materials is thermally activated and least-squares fits to Eq.(1) yield the activation parameters compiled in Table 3. There are some notable deviations from a linear $\ln \sigma$ vs. $1/T$ relationship (e.g., $[\text{Si}(\text{Pc})\text{O}]\text{TCNQ}_{0.5}]_n$) and further investigations of the reasons for this behavior are in progress. Infrared spectral studies of the TCNQ-doped materials reveal a displacement of ν_{CN} to lower frequencies [41], consistent with electron density uptake by the quinone [42]. Clearly partial oxidation of the phthalocyanine stack by high potential quinones occurs when a segregated stack structure is enforced.

In principle, it should also be possible to partially reduce phthalocyanines and to create conducting materials by injecting nonintegral amounts of electron density per site [41]. A number of attempts have been made to partially reduce metallophthalocyanines using alkali metals [20]. In all cases, the resulting materials are insulators, and it was suspected that non-stacked materials were being produced. A preliminary experiment

TABLE 3

Electrical Conductivity Data for Polycrystalline Samples of
Cofacial Phthalocyanine Polymers with Various Dopants

<u>Dopant^a</u>	<u>Empirical Formula</u>	<u>$\sigma(\Omega^{-1} \text{ cm}^{-1})_{300^\circ \text{K}}$</u>	<u>Activation Energy(eV)</u>
none	$[\text{Si}(\text{Pc})\text{O}]_n$	3×10^{-8}	
I	$\{[\text{Si}(\text{Pc})\text{O}]\text{I}_{1.55}\}_n$	1.4	$0.04 \pm .001$
Br	$\{[\text{Si}(\text{Pc})\text{O}]\text{Br}_{1.00}\}_n$	6×10^{-2}	
K	$\{[\text{Si}(\text{Pc})\text{O}]\text{K}_{1.0}\}_n$	2×10^{-5}	
TCNQ	$\{[\text{Si}(\text{Pc})\text{O}]\text{TCNQ}_{0.50}\}_n$	2.8×10^{-3}	$0.09 \pm .002$
Flr	$\{[\text{Si}(\text{Pc})\text{O}]\text{Flr}_{0.23}\}_n$	7.2×10^{-4}	$0.13 \pm .001$
Chl	$\{[\text{Si}(\text{Pc})\text{O}]\text{Chl}_{0.037}\}_n$	6.9×10^{-4}	$0.13 \pm .002$
Brl	$\{[\text{Si}(\text{Pc})\text{O}]\text{Brl}_{0.84}\}_n$	5.8×10^{-4}	$0.15 \pm .001$
DDQ	$\{[\text{Si}(\text{Pc})\text{O}]\text{DDQ}_{1.00}\}_n$	2.1×10^{-2}	$0.08 \pm .001$
DDQ	$\{[\text{Si}(\text{Pc})\text{O}]\text{DDQ}_{0.35}\}_n$	6.2×10^{-2}	$0.05 \pm .001$
DHB	$\{[\text{Si}(\text{Pc})\text{O}]\text{DHB}_{0.13}\}_n$	3.8×10^{-5}	$0.19 \pm .005$
ClA	$\{[\text{Si}(\text{Pc})\text{O}]\text{ClA}_{0.14}\}_n$	1.8×10^{-3}	$0.11 \pm .001$

^a Flr = fluoranil; Chl = chloranil; Brl = bromanil; DDQ =
dichlorodicyanoquinone; ClA = chloranilic acid.

was conducted in which $[\text{Si}(\text{Pc})\text{O}]_n$ was reacted with potassium vapor in a sealed tube. The product was collected and handled at all times in an inert atmosphere. As can be seen in Table 3, a significant increase in electrical conductivity accompanies the potassium doping. Further efforts to refine the reductive doping procedure are now in progress.

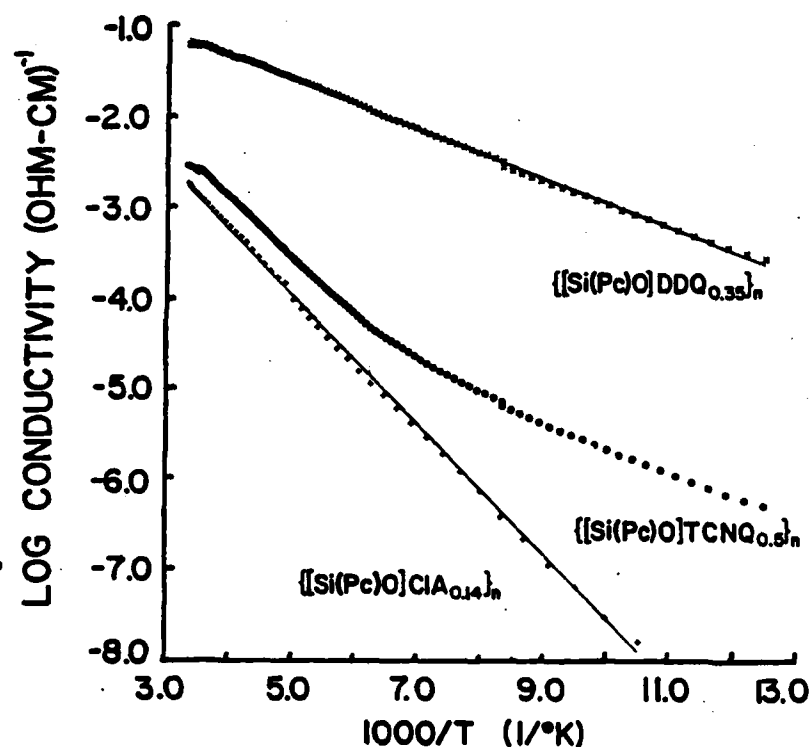
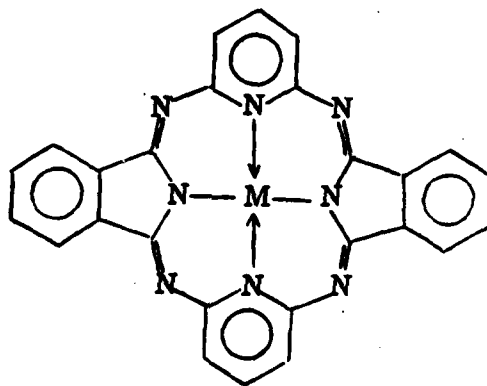


FIGURE 8. Variable temperature powder conductivities of the siloxane phthalocyaninato cofacial polymer doped with high potential quinones. CIA = chloranilic acid.

SYNTHESIS AND HALOGEN DOPING OF COFACIALLY LINKED METALLO-HEMIPORPHYRAZINES

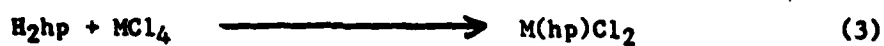
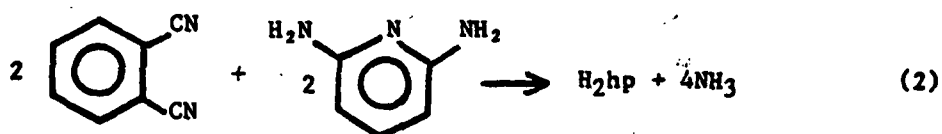
It has also been of interest to elaborate the face-to-face conducting polymer concept to include other types of metallomacrocycles. A particularly intriguing question concerns whether such an approach could bring macrocycles which do not normally stack into a cofacial orientation and what the properties of

- the resulting materials would be. Previous results in this Laboratory indicated that metallohemiporphyrazines (M(hp), shown below) could be oxidized with iodine when $M = Ni$ but the products



M(hp)

remained insulating [44]. Since the molecular orbital topology of the hemiporphyrazine ligand, as probed by molecular orbital calculations at the Pariser-Parr-Pople SCF LCAO CI π -electron level [45,46], is considerably different from phthalocyanines [45] (both HOMO and LUMO are more localized in H_2hp [46]), it was of interest to explore the effect of enforced molecular stacking on oxidation state and charge transport. Face-to-face silicon and germanium hemiporphyrazine macromolecules, [46-48] were synthesized as depicted in Eqs.(2)-(5). The macromolecules were characterized



M = Si, Ge

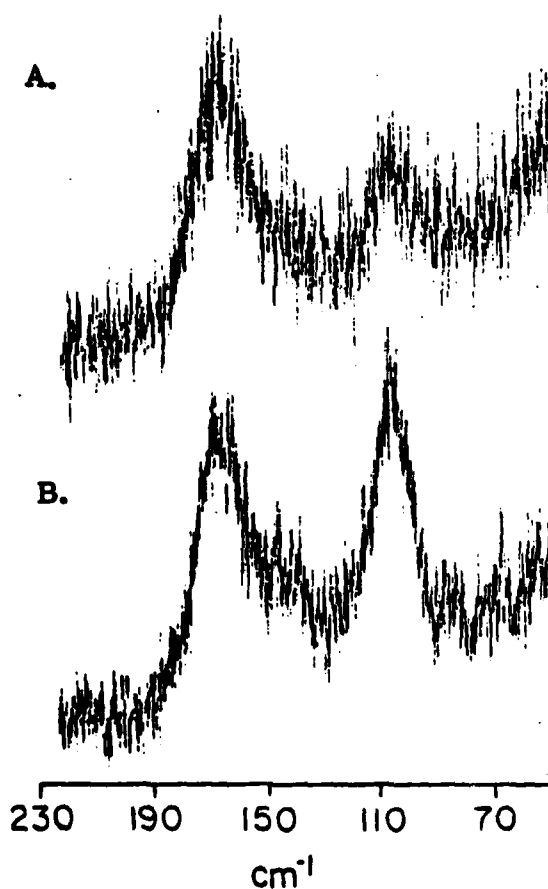


FIGURE 9. Resonance Raman spectra ($\nu_0 = 5145 \text{ \AA}$) of A. $[\text{Si}(\text{hp})\text{O}]_{1.51}_n$ B. $[\text{Ge}(\text{hp})\text{O}]_{1.48}_n$ as polycrystalline samples.

by elemental analysis and vibrational spectroscopy. The available structural data [47,49] indicate that $[M(\text{hp})\text{O}]_n$ interplanar spacings should be comparable to those for the $[M(\text{Pc})\text{O}]_n$ materials. Iodine uptake was not as facile as for the $[M(\text{Pc})\text{O}]_n$ macromolecules, and very large excesses of iodine as well as heating of the sample were required to achieve significant dopant levels ($\{[M(\text{hp})\text{O}]I_x\}_n$ where $x > 1$). Resonance Raman spectra (Figure 9) do indicate that oxidation has occurred in the $x \approx 1.5$ materials, yielding formally mixed valent cofacial arrays, but the degree of oxidation per added equivalent of iodine does not appear to be as great as for the phthalocyanine analogues. ESR spectra indicate the formation of π radical cations (Table 4), and the

TABLE 4

Powder ESR and Conductivity Data for Iodinated Hemiporphyrizine Cofacial Polymers

Compound	$g(300^\circ\text{K})^a$	$\Gamma(300^\circ\text{K})(G)^b$	$\sigma(\Omega^{-1}\text{cm}^{-1})(300^\circ\text{K})$
$[\text{Si}(\text{hp})\text{O}]_n$			$<10^{-12}$
$\{[\text{Si}(\text{hp})\text{O}]I_{1.51}\}_n$	2.003	7.8	3.0×10^{-8}
$[\text{Ge}(\text{hp})\text{O}]_n$			$2.0 \times 10^{-16}^c$
$\{[\text{Ge}(\text{hp})\text{O}]I_{1.48}\}_n$	2.003	6.2	6.0×10^{-9}

^a Average g-value; g_{\parallel} and g_{\perp} are not resolved.

^b Observed linewidth

^c G. Meyer and D. Wöhrle, Makromol. Chem., **175**, 714 (1974).

measured g-values are not greatly different from the aforementioned phthalocyanine polymers. Thus, oxidation involves orbitals which are predominantly ligand in composition. Room temperature pressed powder conductivity data are also given in Table 4. A significant increase in conductivity occurs upon iodination,

however charge transport values are still many orders of magnitude below those for the analogous cofacial phthalocyanines. In some respects the situation is similar to the halogenated glyoximates, which form mixed valent stacks but are only semiconducting [8,11,12]. Mixed valency and cofacial stacking are clearly a necessary but not sufficient condition to form a highly conductive macromolecule.

CONCLUSIONS AND PROSPECTS

Cofacial metallomacrocycle assembly techniques represent what is likely the most powerful approach yet developed for controlling molecular stacking architecture in low dimensional materials. In terms of fundamental understanding, we already have learned a great deal about bandwidth-conductivity and donor-acceptor relationships in conductive materials composed of molecular stacks. However, the surface has only been barely scratched in terms of the exciting research opportunities which await exploitation in this area. Further synthetic work offers the opportunity to make drastic changes in macrocycle identity and electronic structure, stacking distance and bandwidth, interplanar relationships and phonon dynamics, and to correlate these chemical modifications with physical observables. Already, efforts to introduce new metal ions [50,51] and bridging functionalities [23,52] have succeeded. Studies with new types of dopants should provide much important information on donor-acceptor relationships and on the cohesive forces which stabilize the mixed valent state. A wide variety of magnetic, charge transport, and optical experiments remain to be carried out which should ultimately provide invaluable information on how the chemistry and lattice architecture

are related to some of the fundamental characteristics of the molecular metallic state. Finally, little is known about the processing and fabrication properties of these new classes of materials. Efforts in this direction are presently underway and should provide interesting and useful information of technological relevance.

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